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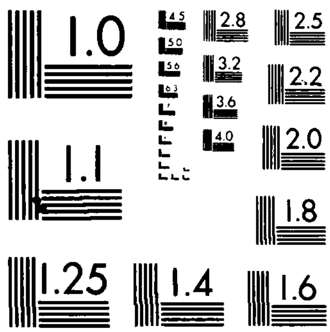

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EXPERIMENTAL STUDY OF CHEMICAL ALLEVIATION FOR IMPROVING REENTRY COMMUNICATION

by

Zonghou Chu, Boyi Wang, and Lie Lin

FOREIGN TECHNOLOGY DIVISION

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Experimental Study of Chemical Alleviation for Improving Reentry Communication*

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ABSTRACT

Chemical alleviation for improvement of reentry communication by solid ablation and liquid injection has been a practical technique. The mechanism of chemical alleviation and the method of experimental studies of simulation in an arc tunnel are discussed in this paper. Experiments are performed in the H11DF arc tunnel by two diagnostic methods which are the microwave method and the probe method. From the experiments, the effects of ablative products from the heat-protection material upon the electron concentration in the flow field and upon the transmission of the electromagnetic wave and the effect of the injection of different electrophilic reagents upon the electron concentration in the flow field are determined. This has provided the basis for selecting the heat-protection materials and determining their properties.

*Received February 4, 1983

I. Introduction

When a high velocity aircraft reenters the earth's atmosphere, part of its kinetic energy will transfer into the internal (or thermal) energy of the surrounding air molecules due to the surface friction and the compressive heating by the shock wave. The air temperature between the shock wave and the aircraft can reach several thousand degrees such that the neutral molecules will be ionized into ions and free electrons and then a plasma is formed. These charge particles may drift to the rear of the aircraft and form a long bright tail of hot plasma whose length is about several ten times of the aircraft's diameter. This ionized molecule layer which is surrounding the reentering aircraft is usually called "reentry plasma sheath".

Inside the reentry plasma sheath, there are a large amount of free electrons. Since the electromagnetic wave will be absorbed, reflected, or scattered by the free electrons, these free electrons can interfere or even worse can interrupt the transmission of the electromagnetic waves. The interruption of reentry communication had been found in the reentries of the intercontinental missile, returning earth satellite, and space shuttle. The interruption sometimes lasts as long as 15 minutes. Therefore the interruption of reentry communication is a difficult problem for the design of aircraft and remote control apparatus on the ground. This is hard to be overcome especially for the mission of instant signal transmission, e.g., electronics competition and induced explosion, object identification, and language communication, etc. This is also the common problem faced by all countries who want to develop the strategic

guided missiles and the aerospace technology.

There already are some methods to improve the reentry communication.[1-5] In this paper, we will study the mechanism of chemical alleviation for improving the reentry communication and will investigate the experimental methods of simulation in an arc tunnel. The methods of the probe and the microwave are employed here as the diagnostic techniques. From the experiments we are able to determine the effect of the ablative products from various heat-protection materials upon the electron concentration inside the flow field and upon the transmission of electromagnetic waves. The effect of the injection of various electrophilic reagents upon the electron concentration in the flow field is also studied in this paper. Our experimental data will be compared with those data measured in the free flight.[6,7] The primary simulation parameters for the interruption of reentry communication in the reentry plasma sheath are the electron concentration and collision frequency. The arc tunnel of high enthalpy and low density can satisfy the requirements of the simulation under certain conditions.

II. Mechanism of Chemical Alleviation

When the electromagnetic waves pass through the plasma, the charged particles of the plasma are forced to oscillate by the electromagnetic waves. The energy consumed by the oscillation is inversely proportional to the mass of the charged particles. Their relation is

$$W(t) - W(0) = \frac{1}{2M_e}\left(\frac{eE_0}{\omega}\right)^2(\cos\omega t - 1)^2 \qquad (1)$$

where W(t) and W(0) are the kinetic energies of the charged

particles at time t and 0, respectively, M_c is the mass of the charged particle, e is the electron charge, E_0 is the amplitude of the alternative electric field, and ω is the angular frequency of the electric field. Since the mass of the atom is about three orders of magnitude larger than that of the electron, the electrons consume most of the energy of the electromagnetic waves. Therefore the transmission of the electromagnetic wave through the plasma can be enhanced by attaching these electrons to the neutral molecules to form the negative ions.

Chemical alleviation can be achieved by adding some special heat-protection materials or injecting some electrophilic liquid to the upstream of the antenna window of the reentering aircraft. These electrophilic addenda entering into the reentry plasma sheath will attach the free electrons and form negative ions. The electron concentration in the plasma sheath will decrease such that the electromagnetic waves can transmit through the plasma sheath. In general, the atoms or molecules which have a high ionization potential will have high electron affinity for their negative ions. As shown in Fig. 1, the alkali metals and the alkaline earth metals have low ionization potential and are easy to be ionized. On the other hand, the halogen elements have high ionization potential and then have strong electron affinity. Therefore the halogenides such as polymeric tetrafluoroethylene, freon, sulfur hexafluoride, and carbon tetrachloride, etc. are all good candidates for chemical alleviation. For ablative alleviation, the concentration of the alkali metals and the alkaline earth metals in the ablator should be reduced. But some electrophilic chemicals should be added to the ablator to form a

compound material. This compound material under the high temperature of the plasma sheath will be ablated and those electrophilic elements will flow into the plasma sheath and attach the free electrons. For injecting alleviation, the electrophilic liquid is injected into the plasma sheath by a pumping system. The injected liquid is deflected by the high speed air flow and becomes small fragment drops. These drops will quickly vaporize and react with the gases inside the plasma sheath. The electron concentration in the plasma sheath can thus be reduced by this method.

There are three primary physical and chemical processes involved in the chemical alleviation. The first process is the multi-phase recombination process. The surface of the third body which is the liquid drop serves as a catalytic surface. The recombination rate between the ions and electrons can be enhanced on this surface. During the change from the liquid phase to gas phase, the liquid absorbs energy and cools down the gases. This process also can increase the recombination rate between the electrons and ions. The second process is the process of charging liquid drops. Due to the random thermal motion of the ions and electrons inside the plasma sheath, it is possible that the free electrons may stick to the liquid surface. The liquid drops will thus be negatively charged and have stronger surface electric fields. After these liquid drops vaporize, negative ions are produced. The third process is the attaching process in gas phase. Most of the alleviators in the sheath, after going through various chemical reactions at the high temperature and

high velocity gas flow, will produce some electrophilic atoms, molecules, and compounds. These particles have high electron affinity and can attach electrons to form stable negative ions. These are the main processes for chemical alleviation. Now we choose polymeric tetrafluoroethylene as an example to explain the chemical reaction processes in the sheath. When the temperature exceeds 1000 °K, the polymerictetrafluoroethylene will dissociate into monomolecule rapidly as follows:

$$-(CF_2 - CF_2)_n \xrightarrow{\text{high temperature}} n\, C_2F_4 \qquad (2)$$

The tetrafluoroethylene molecule will react with the gases inside the sheath. The majority of the gases inside the sheath are N_2, N, and O. Tetrafluoroethylene may collide with N_2 or N and dissociate:

$$C_2F_4 + M \rightarrow 2CF_2 + M \qquad (3)$$

where M is either N_2 or N. Tetrafluoroethylene may collide and be oxidized by the oxygen atom, too :

$$C_2F_4 + O \rightarrow CF_4 + CO \qquad (4)$$

CF_2 and CF_4 also can react with some other gas elements:

$$CF_2 + M \rightarrow CF + F + M \qquad (5)$$

$$CF_4 + M \rightarrow CO + 2F_2 \qquad (6)$$

$$CF_4 + O \rightarrow CF_2O + 2F \qquad (7)$$

$$CF_2 + O \rightarrow CO + 2F \qquad (8)$$

$$F + e \rightarrow F^- \qquad (9)$$

In fact, the concentration of each gas elements is determined by the partial pressures of the air and the ablative products inside the sheath, by the variation of the thermal energy with respect to time, and by the reaction time.

In order to assess the effectiveness of each alleviator quantitatively, a simple analysis is described below. The reaction between the alleviator and the free electrons takes place in the gas phase. Its reaction process is reversible.

$$A + e \underset{k_b}{\overset{k_a}{\rightleftharpoons}} X^- + Y \qquad (10)$$

where A, e, X^-, and Y represent the alleviator, free electron, negative ion, and neutral product. The forward process in Eq. (10) is the attachment process which will take out the electrons. k_a is the electron attachment rate constant. On the other hand, k_b is the electron detachment rate constant of the backward process. In the plasma, the rate equation for the number of free electrons can be expressed as follows:

$$\frac{dN_e}{dt} = -k_a N_a N_e + k_b N_X N_Y \qquad (11)$$

where N_e, N_a, N_X, and N_Y are the numbers of the free electrons, alleviator, negative ions, and forward reaction products, respectively, and t is the reaction time. For alleviators, it is always true that $k_a >> k_b$. So the last equation can be simplified to

$$\frac{dN_e}{dt} = -k_a N_a N_e \qquad (12)$$

According to the conservation law of the numbers of particles,

$$N_a(0) - N_a = N_e(0) - N_e \qquad (13)$$

where $N_a(0)$ and $N_e(0)$ are the initial number of alleviator and free electron, respectively. Substitute Eq. (13) into Eq. (12) and integrate it, then we have

$$\frac{N_e}{N_e(0)} \frac{N_a(0)}{N_e + [N_a(0) - N_e(0)]} = \exp\{-[N_a(0) - N_e(0)] k_a t\} \qquad (14)$$

If the number of the electrons decreases remarkably after the reaction, i.e., $N_e(0) >> N_e$, then the last equation can be simplified to

$$\frac{N_e}{N_e(0)} = \frac{N_a(0) - N_e(0)}{N_a(0)} exp\{-[N_a(0) - N_e(0)]k_a t\} \qquad (15)$$

If $N_e/N_e(0)$ is used for the assessment of the effectiveness of the alleviation, the most important factors can be seen from the last equation. They are: electron attachment rate constant k_a, initial number of the alleviator $N_a(0)$, and reaction time t.

The negative ion produced from the electrophilic molecule sometimes is not stable. Especially at high temperature, it may loose the electron again. This is the backward detachment process. The stability of the negative ion is determined by its electron affinity. The higher the electron affinity is, the higher the work needed to remove an electron from the negative ion is. The negative ions of the halogen elements are very stable because their electron affinities are very high.

III. Experimental Apparatus and the Diagnostic Methods

We use the H11DF arc tunnel for the experimental studies of the simulation. This tunnel has the properties of high enthalpy and low density. Fig. 2 is the schematic diagram of the tunnel and Table 1 given operation parameters of the tunnel. Nitrogen gas is heated by a heater before it enters the mixing room, but oxygen gas is fed into the mixing room directly. They are mixed in the mixing room according to their partial pressure ratio in the air. This mixed gas is then injected into the test chamber by an ultrasonic nozzle. The properties of the flow field are measured in this test chamber. For the experiment of ablative

alleviation, the worm and worm gear mechanics, which is driven by a servo motor, sends the specimen into the mixing room for ablation. In this case, the ablative products will exist in the gas flow, and the properties of the flow field with ablative products can be measured in the test chamber. For the experiment of injecting alleviation, the electrophilic liquid is injected into the gas flow through a nozzle near the ultrosonic nozzle. The direction of injection is perpendicular to the direction of the gas flow. The liquid from the nozzle, which is under the heavy collision of the gas flow at ultrasonic speed, will become foggy drops and mix with the gas molecules flowing down stream. So, the properties of the flow field with injecting liquid can be measured in the test chamber. Our arc tunnel can be operated stably and continuously for a long period. For each operation, we can measure the variation of the microwave transmittance and the electron concentration inside the pure flow field and the flow field with ablative products or injecting liquid simultaneously.

In order to obtain experimental data accurately, we employ two plasma diagnostic techniques, namely the probe method and the microwave method, and compare these two results with each other. At first, we measure the electron concentration in the pure flow field . Then we determine the alleviation after the alleviators are added.

The electrostatic probe is a cylindrical iridium wire with a diameter of 0.5 mm and a length of 10 mm. A series of tests can be done by moving the probe along the axis of the flow field.

The probe is charged by an external power supply and the cover layer of the tunnel is used as the compensating electrode. The measured current(A) varies as the applied voltage (V) changes. The V-A characteristic curve can thus be obtained. This characteristic curve is dependent on the electron concentration and the temperature of the plasma . Their quantitative formula can be derived from the probe theory. Figure 3 shows the V-A characteristic curve measured by the probe method. The advantages of the probe method are that the experimental set up is simpler, it has wide dynamical range, and all points and their distribution can be measured. Its disadvantages are that the flow field will be interfered by the probe and that the surface of the probe will be corroded by the ablative products and the accuracy of the measurement will be affected.

It is easier to measure the electron concentration in the pure flow field by the probe method. This is because the pure flow field has the same concentration of electrons and ions. But when the ablative products or injecting liquid are inside the flow field, the V-A characteristic curve will change because of the existence of the negative ions. In this case, the saturation current of the positive probe (cnotributed from the electrons and the negative ions) will decrease remarkably. However, the saturation current of the negative probe (contributed from the positive ions) will increase slightly. If the concentration of the negative ions in the flow field is very high, the characteristic curve of the single probe is almost close to symmetry. In this case, only the floating potential method can be used to determine the electron concentration. According to

our experimental conditions, the relation between the electron concentration and the floating voltage is simplified as follows:

$$\frac{n_e}{n_{e0}} = \frac{j_i/j_{i0}}{\exp[(e/kT_e)(V_{f0} - V_f)]} \tag{16}$$

where n_e and n_{e0} are the electron concentration in the flow field with and without alleviator, respectively, $(V_{J0} - V_J)$ and (j_i/j_{i0}) are the difference of the floating voltage and the saturation current ratio of the positive ions with and without alleviator, k is the Boltzmann constant, and T_e is the thermal temperature of the electrons.

By using the transmission property of the microwave inside the plasma, the plasma parameters such as electron concentration and collision frequency can be determined. The advantages of the microwave method are non-contact and fast response. Its disadvantage is that only the integrated or average values can be measured. We use a microwave transmission apparatus with three frequencies of Gz, Xs, and Ka to diagnose the flow field. Its block diagram is shown in Fig. 4. The power transmission coefficient can be measured by this microwave transmission apparatus.

The transmission of the electromagnetic wave inside the plasma is a very complicated problem. For the first order approximation, we simplify our experimental conditions so that only one dimension is considered. We also assume a homogeneous plane wave is normally incident on a homogeneous thick plasma with a boundary and is under no magnetic field. According to the theory of interaction between the microwave and plasma,

several one dimensional equations are derived and are shown below:

$$T = \frac{(1-r)^2\exp(-2\alpha d)}{1-r^2\exp(-4\alpha d)} \tag{17}$$

$$r = \frac{(1-\mu)^2+\chi^2}{(1+\mu)^2+\chi^2} \tag{18}$$

$$\chi = \left\{-\frac{1}{2}\left(1-\frac{\omega_p^2}{\omega^2+\nu^2}\right)+\frac{1}{2}\left[\left(1-\frac{\omega_p^2}{\omega^2+\nu^2}\right)^2+\left(\frac{\omega_p^2}{\omega^2+\nu^2}\,\frac{\nu}{\omega}\right)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} \tag{19}$$

$$\mu = \left\{\frac{1}{2}\left(1-\frac{\omega_p^2}{\omega^2+\nu^2}\right)+\frac{1}{2}\left[\left(1-\frac{\omega_p^2}{\omega^2+\nu^2}\right)^2+\left(\frac{\omega_p^2}{\omega^2+\nu^2}\,\frac{\nu}{\omega}\right)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} \tag{20}$$

$$\alpha = \frac{\omega}{c}\chi \tag{21}$$

$$\omega_p^2 = \frac{4\pi e^2 n_{e0}}{m_e} \tag{22}$$

where T, γ, χ, μ, α, and ω are the power transmission coefficient of the microwave, power reflection coefficient at the boundary, attenuation index, refractive index, attenuation coefficient, and frequency, respectively; ω_p, ν, n_{e0}, and d are the plasma frequency, collision frequency, electron concentration, and effective thickness, respectively; e and m_e are the charge and mass of the electron. For these six equations, there are five known values: T, d, ω, e, and m_e, and there are seven unknown values: γ, χ, μ, α, ω_p, ν, and n_{e0}. By using the diagnostic technique of double-frequency transmission and the calculation method of overlap-substitution, the power transmission coefficient can be measured from two microwave frequencies. The electron concentration in the flow field and the collision frequency can then be determined.

IV. <u>Discussion</u>

The ablative alleviation and the injecting alleviation are investigated separately under the stable operation of the H11DF

arc tunnel. Our goals are: first of all to study the feasibility of the ground simulation in the arc tunnel and the reliability of our diagnostic methods; secondly to study the effect of the ablative products from the compound material which contains different alleviators upon the microwave transmittance, and to find out the best compound material which has the best alleviation; thirdly to determine the effect of various impurities in the heat-protection material upon the electron concentration in the flow field, which can be used as the reference for the material technology; finally to study the effect of various injecting electrophilic liquids upon the electron concentration in the flow field and to choose the best liquid alleviators. After several hundred times of experiments, we have reached our expected goals which are described below.

1. For the measurement of the electron concentration in the flow field: It is 3.0×10^{11}/c.c. which was measured by the probe method. The average value measured by the microwave transmission apparatus with three frequencies is 3.3×10^{11}/c.c.. These two results agree very well. The collision frequency in the flow field measured by the microwave method is 3×10^{9}/sec.

2. Figure 5 is the power transmission coefficient at different microwave frequency when the microwave transmits through the flow field. As shown in the figure, the power transmission coefficient increases by increasing the microwave frequency.

3. Figure 6 shows the effect of the ablative products of the compound material which contains polymeric tetrafluoroethylene upon the microwave transmittance, where X is the fraction of

polymeric tetrafluoroethylene in the compound material, $\dot{m}_\ell$ and $\dot{m}_f$ are the material's ablation rate and the mass flux of the gas, respectively. As shown in the figure, the alleviation increases by increasing the fraction of the polymeric tetrafluoroethylene.

4. Figure 7 shows the effect of four different kinds of liquid alleviators upon the electron concentration in the flow field, where $\dot{m}_\ell$ is the injection rate of the liquid alleviator. As shown in the figure, the alleviation increases by increasing the injection of the alleviator. It should be noted that freon has the best alleviation.

5. Table 2 lists our experimental data and the experimental data of the free flight.[5] As can be seen from the table, these two data are basically consistent with each other for polymeric tetrafluoroethylene and freon. We thus conclude that the chemical alleviation experiment in the arc tunnel is a good simulation method and is worth further study.

ACKNOWLEDGMENTS

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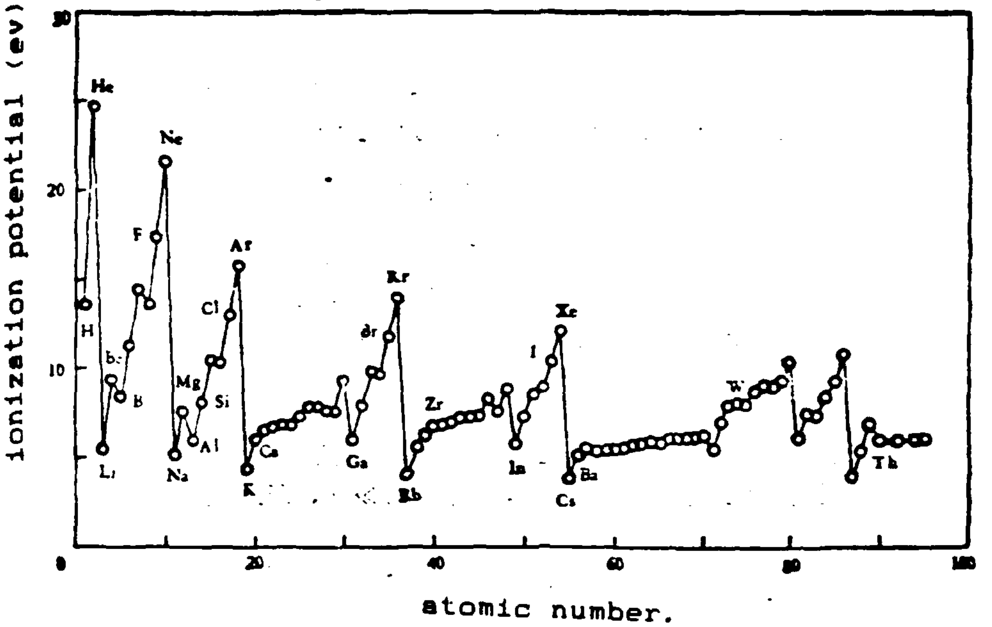

Fig. 1 The ionization potentials of the atoms.

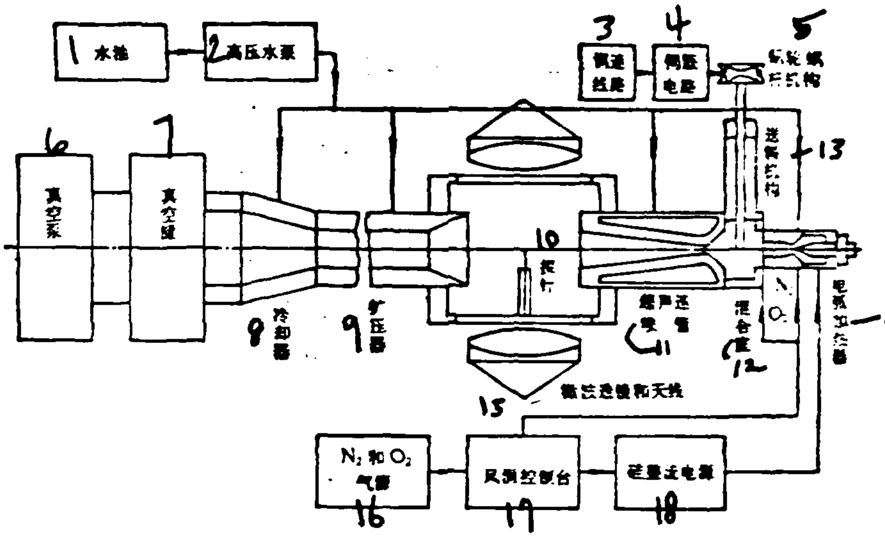

Fig. 2 The schematic diagram of the HIIDF arc tunnel.

1. water pool; 2. high pressure water pump; 3. modulating speed circuit; 4. servo circuit; 5. worm and worm gear mechanics; 6. vacuum pump; 7. vacuum room; 8. cooler; 9. pressure expander; 10. probe; 11. ultrasonic nozzle; 12. mixing room; 13. delivery mechanics; 14. arc heater; 15. microwave lens and antenna; 16. gas supplier; 17. tunnel control board; 18. silicon rectifying power source.

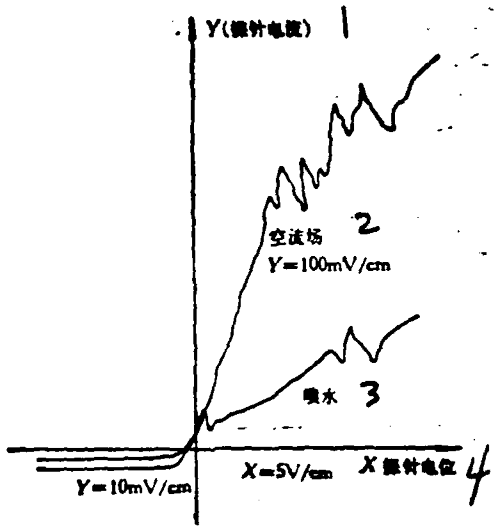

Fig. 3 The V-A characteristic curves of the pure flow field and the flow field with water vapors. The curves are measured by the electrostatic probe.

1. probe current; 2. pure flow field; 3. water vapor; 4. probe voltage.

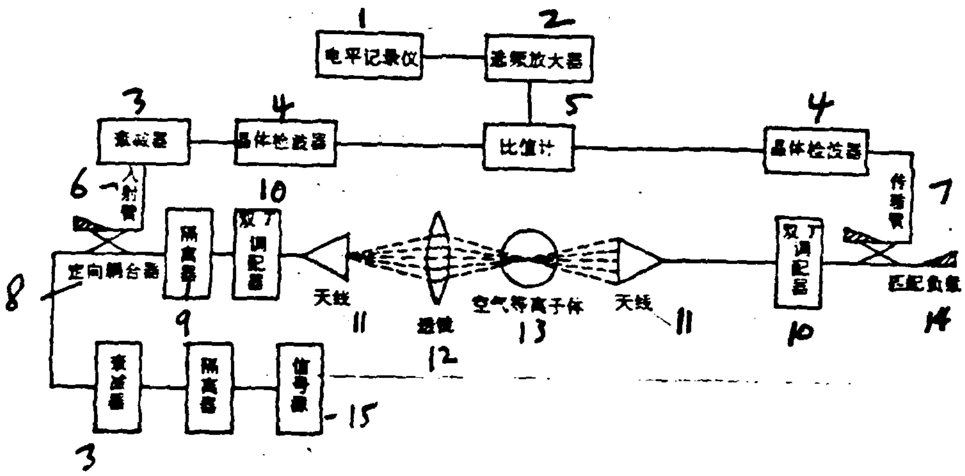

Fig. 4 The block diagram of the microwave transmission apparatus.

1. recorder; 2. amplifier of selective frequency; 3. attenuator; 4. crystal microwave detector ; 5. comparator; 6. injection arm; 7. transmission arm; 8. directional coupler; 9. separator; 10. double-T modulating distributor; 11. antenna; 12. lens; 13. air plasma; 14. distribution load; 15. signal source.

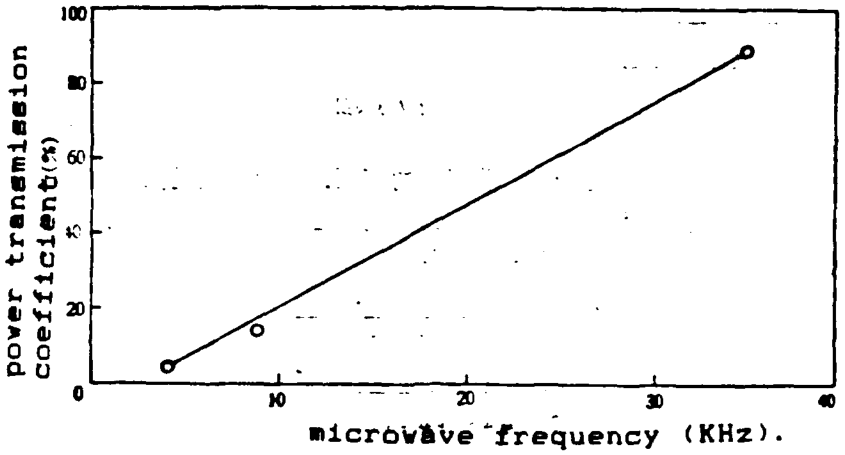

Fig. 5 The power transmission coefficient vs microwave frequency inside the air plasma.

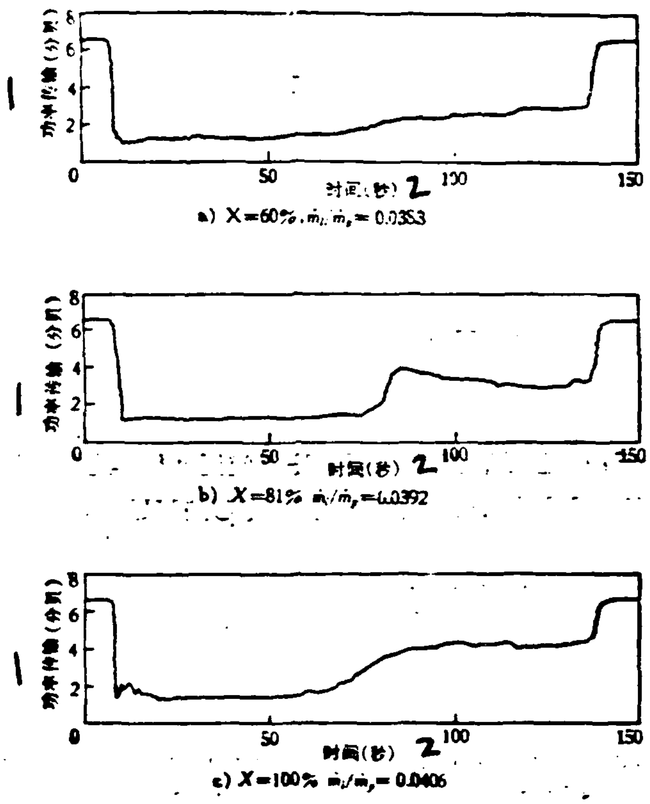

Fig. 6 The effect of the ablative products from the compound material which contains polymeric tetrafluoroethylene upon the microwave transmittance.

1. power transmittance (db); 2. time (sec).

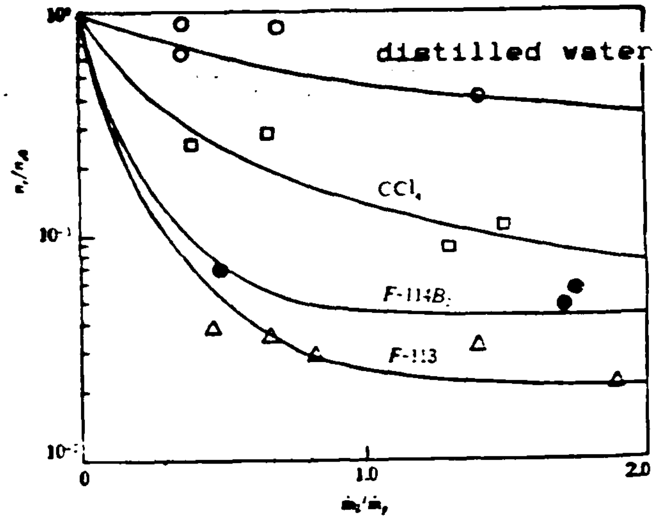

Fig. 7 The effect of the injection of the electrophilic liquid upon the electron concentration in the flow field.

Table 1. The operating parameters of the H11DF arc tunnel.

Arc Heater		Mixing Room		Test Chamber	
Arc Voltage	90 V	Total Enthalpy	5800 cal/g	M_a Number	5.4
Arc Current	250 amp	Temperature	6800 °K	Static Pressure	1 Torr
Arc Power	22.5 KW	Total Pressure	0.658×10^5 nt/m^2	Static Temperature	900 °K
Mass Flux of Nitrogen	0.36 g/sec	Electron Concentration	10^{14} /c.c.	Gas Density	6×10^{-7} g/c.c.
		Mass Flux of Oxygen	0.11 g/sec	Total Mass Flux of Gases	0.47 g/sec
				Electron Concentration	10^{11}/c.c.

Table 2. The Comparison between the experimental data of the arc tunnel and the experimental data of the free flight.

Addenda	Data of Free Flight		Data of H11DF Tunnel	
	$\dot{m}_\ell / \dot{m}_p$	n_ℓ (1/c.c.)	$\dot{m}_\ell / \dot{m}_p$	n_ℓ (1/c.c.)
None	0	$\sim 10^{11}$	0	$\sim 10^{11}$
Polymeric Tetrafluoroethylene	0.033	$\sim 10^{9}$	0.5	$\sim 10^{9}$
Freon	0.646	$\sim 10^{8}$	1.0	$\sim 10^{9}$

Abstract

Chemical alleviation for improvement of reentry communication by solid ablation and liquid injection has been a practical way. The mechanism of chemical alleviation and the method of experimental studies of simulation in an arc tunnel are discussed in this paper. Studies have been performed in the H11DF arc tunnel by diagnostic methods of heat-protection material upon the electron concentration and the microwave transmission, and the injection of different electrophilic reagents upon the electron concentration have been determined. This has provided basis for selection heat-protection materials and identifying their properties.

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